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STEREOLITHOGRAPHY: EQUIPPING THE INTEGRATED PRODUCT TEAM

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During the Government's attempts to streamline the acquisition process, several new concepts and ideologies have emerged. It was apparent that producing an affordable system meant designing with production in mind. To accomplish the, the producers and manufacturers had to be involved early in the life cycle, working hand in hand with the designers.

In this report, we will focus on the specific asset, Stereolothography (SL), and its application within the Enhanced Fiber Optic Guided Missile (EFOGM) Seeker Integrated Product Team (IPT). The benefits derived by the EFOGM Seeker IPT, a rapid prototyping tool, were beyond expectation. We hope to illustrate the necessity of employing such tools early in design and development.

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Also, we would like to express our gratefulness to the entire Team EFOGM Seeker IPT and Electro-Optical IPT. It was their foresight and willingness to use these SLA models that made the effort a success.

TABLE OF CONTENTS

		Page
I.	INTRODUCTION	1
II.	THE STEREOLITHOGRAPHY PROCESS	2
	A. The CAD Model	2
	B. Support Generation	2
	C. Slicing	2
	D. Building	3
	E. Post Processing	3
III.	PROGRAM BACKGROUND	4
IV.	CFT SEEKER ANALYSIS AND LESSONS LEARNED	5
V.	TACTICAL SEEKER ANALYSIS AND LESSONS LEARNED	9
VI.	SECOND TACTICAL SEEKER	10
VII.	OTHER EFOGM SLA EFFORT	11
VIII.	SUMMARY	13
	BIBLIOGRAPHY	14

I. INTRODUCTION

During the Government's attempts to streamline the acquisition process, several new concepts and ideologies have emerged. Practices such as concurrent engineering, producibility engineering, and planning and design to unit production cost became the guidelines for designing a producible and fieldable military system. It was apparent that producing an affordable system meant designing with production in mind. To accomplish this, the producers and manufacturers had to be involved early in the life cycle, working hand in hand with the designers. Until recently, however, all of these remedies were directed at the contractors with the Government possessing only a management position, if a position at all.

During the 1990's, a new practice became the standard of Government acquisition, Integrated Product and Process Development (IPPD). The IPPD philosophy encompasses all the proven concepts of old, but adds a new factor into the equation. The IPPD approach requires Government representatives to be involved in the design and development from day one. The IPPD philosophy is implemented through the Integrated Product Team (IPT). This IPT is a collection of both contractor and Government personnel from all engineering disciplines, design, quality/product assurance, production/manufacturing, test, etc. The IPPD methodology allows the IPT to draw from the personnel, experience, and assets of both the Government and industry.

In this report, we will focus on a specific asset, Stereolithography (SL), and its application within the Enhanced Fiber Optic Guided Missile (EFOGM) Seeker IPT. This rapid prototyping tool is owned and operated by the U.S. Army Aviation and Missile Command and was made available to the IPT through funding provided by the EFOGM Program Management Office (PMO). The benefits derived by the EFOGM Seeker IPT, from this technology, were simply beyond expectation. We hope to illustrate to, the reader, the necessity of employing such tools early in design and development.

II. THE STEREOLITHOGRAPHY PROCESS

Stereolithography is a rapid prototyping technology that quickly and inexpensively produces a plastic prototype directly from a Computer Aided Design (CAD), solid or surface model. The advantage of the SL technology is that it allows the designer to evaluate and improve the design without having to commit the time and financial resources required by conventional machine shop prototyping. This represents a substantial time-savings, since SL can produce a prototype in a matter of days or weeks verses metal prototyping which can take months. The cost savings of SL are equally impressive. SL can save as much as two-thirds the cost of conventional prototyping of very complex parts. And, if design errors are discovered with SL early in the process, the cost savings multiplies dramatically. The Stereolithography Apparatus (SLA) uses a 5-step process to build each prototype.

A. The CAD Model

The SLA requires a tessellated surface model called a .STL file. The .STL file represents a three-dimensional (3-D) surface or solid CAD model using a series of triangles. Most current versions of CAD software are capable of generating .STL files. The CAD packages used to generate the .STL files for the EFOGM effort included Aries, Pro/Engineering, Autocad, and Intergraphics.

B. Support Generation

Each part requires supports for all down facing surfaces. Supports act like fixtures in more conventional operations. They hold the prototype in place during the building process. The supports are generated automatically by the SLA software and are built along with the prototype.

C. Slicing

The SLA software slices the part file into a series of horizontal cross-sections ranging in thickness from 0.004 to 0.006 inches. This thickness is constant for each layer in a given part. The smaller the cross-section thickness, the better the resolution of most SL prototypes. The supports generated for the model are also sliced, with the same cross-section thickness, and merged with the sliced .STL file. This merged file is what the SLA uses to build the prototype, cross-section by cross-section.

D. Building

The build process uses these cross-sections of the part as patterns. A laser beam traces out and fills in each of these cross-sections on the surface of a vat of liquid photocurable resin. Wherever the laser traces, the liquid resin is cured to a solid, to a depth of approximately 0.006 to 0.009 inches. Once the entire cross-section is cured, the part is dipped into the liquid to recoat the part with liquid resin. The laser then traces out the next cross-section on top of the previous one. This process is repeated until all of the cross-sections of the part have been cured. At which time, the completed prototype part emerges from the liquid. The SLA can build extremely complex 3-D parts because it breaks these parts down into a series of relatively simple Two Dimensional (2-D) cross-sections. Therefore, the SLA can produce prototypes of a complex part, that would normally require an expensive multiaxis machine, almost as easily and inexpensively as a very simple part.

The size of any individual part is limited to the size of the vat of liquid resin, which in the case of the MICOM SL lab, is 10 X 10 X 10 inches. Larger parts can be built by cutting the .STL file into smaller parts and building them separately. These smaller parts are then assembled together to form the original continuous part. The Production Engineering Division (PED) has used this method to construct continuous parts as long as 36 inches.

E. Post Processing

Following the build process, the parts are cleaned and the supports are removed. The parts are then placed in an ultraviolet oven to cure any remaining uncured resin inside the part. The parts are usually lightly sanded and bead blasted to achieve a uniform surface texture. If desired, parts can then be painted, dyed, or sprayed with an epoxy clear coat finish.

The accuracy of these SLA parts is usually in the ±0.005 inch range. The SL accuracy is very geometry dependent, unlike traditional machining which is process driven. Most dimensions, which are built in the X-Y plane of the SLA, can be built very accurately, usually within ±0.003 to 0.005 inches. However, the dimensions in the X-Z and Y-Z planes of the SLA usually have an accuracy of about ±0.006 to 0.007 inches.

III. PROGRAM BACKGROUND

The idea of building SLA components was first presented to the EFOGM seeker IPT in late 1995. It was apparent that due to the complexity of the seeker section, not only from a design standpoint but also because of the number of contractors involved, a tool that would complement the CAD database was desperately needed.

At that time, the seeker IPT was preparing for the first Captive Flight Test (CFT). The CFT hardware would consist of a prototype seeker flown in the cargo pod of a commuter airplane. One of the major concerns, in addition to performance, was integration and assembly of the hardware. This concern stemmed from the fact that four different contractors were involved in producing the CFT seeker. Location of these contractors, and the different CAD technologies used at each location, added to the difficulty of integration and assembly analysis. The four contractors involved in producing the CFT seeker were:

1. **Prime Contractor**: **Raytheon Company** (Integration)

Subcontractors:

2. **Southern Research Technologies (SRT)** (Optics and gimbal systems)

3. **Loral Fairchild Systems**, later to become **Lockheed Martin Fairchild Systems (LMFS)** (Focal Plane Array (FPA))

4. **Magnavox** (Dewar)

In addition to these contractors, another subcontractor was being considered to produce an alternative optics system. Not only would this add to the subcontractor chain, but it would also add a foreign contractor, **Pilkington Optronics**, based in Wales.

The IPT also knew that after the CFT, the focus would shift to tactical design. At that time, Raytheon would take over responsibility for producing the Dewar and a new subcontractor, SCI, would be responsible for producing the Seeker Interface Module (SIM). The SIM was not required during CFT. In addition, the basic design of the seeker would change due to stricter tactical size and weight requirements.

While all the benefits of SL were not readily apparent to the IPT, anything lending promise of helping a difficult situation was being pursued. In this light, the IPT requested the EFOGM PMO to provide funding to build the SLA components of the CFT seeker.

IV. CFT SEEKER ANALYSIS AND LESSONS LEARNED

The first SLA build incorporated the SRT optics into the CFT seeker. These parts were completed in February, 1996. The initial response to the SLA components is best described as excitement. For the first time, Seeker IPT members were able to touch and feel hardware, to access features such as hole patterns and connector openings. Interfaces of the various subcontractor's components could immediately be tested. Design flaws such as missing or misaligned features became readily apparent. These models also proved quite beneficial when the Seeker IPT interacted with other IPTs, whose members were not intimately familiar with the design details of the seeker.

When the Pilkington optics development overtook the baseline optics design, it was designated to be flown during the CFT. With this direction, the effort to build the SLA components of the Pilkington optics was initiated. Because of the relatively late start on this effort, the Pilkington SLA components were completed only days before Pilkington shipped the metal parts to LMFS. As the SLA components were completed, problems in the design began to surface. The first problem encountered was the hole patterns were reversed from the LMFS preamp cover to the flat preamp mounting plate on the bottom of the Pilkington optics housing. This same problem existed with the SRT optics and was traced to a misinterpretation of a sketch of the preamp cover. Designers at SRT thought they were looking at the outside of the cover when in fact they were looking at the inside. Since SRT's documentation was sent to Pilkington to be used as interface data, the problem occurred on both sets of hardware.

The situation presented here may seem trivial. However, it illustrates the difficulties in analyzing a 3-D object represented by 2-D media. The SLA components, on the other hand, made it very easy to identify such design errors. In fact, Mr. Lasater, who was unfamiliar with the EFOGM design, was the person who first discovered this particular problem.

Another problem discovered was a missing hole on the Pilkington housing. The hole would allow access to a set screw on a potentiometer shaft which was part of the SRT gimbal system.

Even though both of these issues were discovered in the MICOM SL lab, it was still a surprise to the IPT, including Mr. Minor, that the anomalies existed on the actual hardware. These design flaws were not immediately elevated to LMFS since the IPT was not convinced that these plastic SLA components were exact replicas of the actual hardware. Seeing the same problems appear on the actual hardware at LMFS afforded the IPT a valuable lesson learned for the remainder of the effort. A problem on the SLA components would not be ignored. Any anomaly with the SLA components was due to a design inconsistency in the CAD database or on the actual hardware and in most cases, both.

Both of these design flaws were corrected through relatively simple drilling processes. After the optics assemblies were received at LMFS, the housing was redrilled and the preamp was mounted. Also, the access hole for the set screw was drilled. However, since the optics housing was a part of the optics assembly, as shipped from Pilkington, any machining involved some level of risk. The optics assembly included prescription glass lenses, a delicate drive mechanism, and an exposed objective lens. Any damage to any of these components would render the assembly unusable. This would result in the assembly being shipped back to Pilkington and a major delay in the schedule.

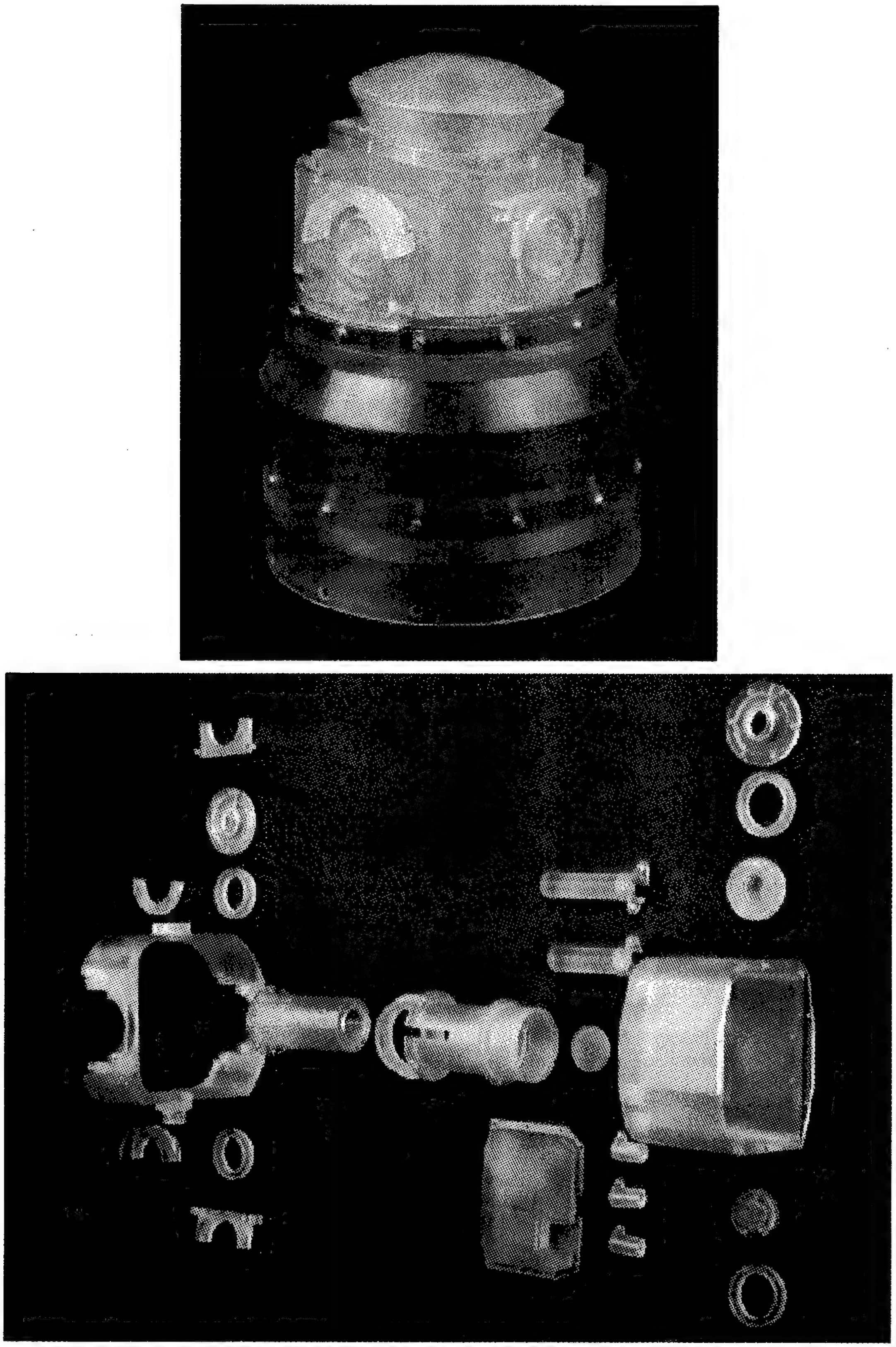
As mentioned earlier, LMFS was responsible for integrating and testing the FPA and its electronics, including the preamp. After the preamp was mounted, a major design issue was discovered. The front plate of the optics housing, which incorporated the objective lens holder, was blocking access to a connector on the preamp. The anomaly was not discovered on the SLA components because the SLA model of the preamp was built from a simplified CAD model. The hole in which the connector would mount was not present on the CAD model and therefore not present on the SLA component.

It was obvious that the housing, with the objective lens in place, had to be machined due to the connector being blocked. Now we were looking at removing metal from the optics assembly. Unlike the corrective drilling mentioned

earlier, machining the assembly would be a very critical operation. Understandably, LMFS was not willing to take responsibility for such a risky procedure to someone else's hardware. The housing would have to be shipped to either Raytheon or Pilkington to have the machining done. As a result, precious days would be lost at LMFS from a schedule that was already being pushed to the limits to make the CFT. However, the SLA models proved to be very useful in correcting the hardware. To minimize impacts to schedule, the SLA components were sent by Raytheon to a machining vendor. The vendor agreed that he could perform the required machining and that the SLA components could be used to perform initial setup and planning. This resulted in the parts being shipped from LMFS, Syosset, NY, to Raytheon, Huntsville, AL, hand carried to the machine shop, machined overnight and shipped back to LMFS the following morning with only a two day slip to schedule. A remarkable feat considering the complexity of this task.

This brings up another very important lesson learned. It is imperative that the exact hardware configuration be built into the SLA components. Because of the immense concerns over packaging, the .STL model of the preamp represented the maximum space available, with only minimal defining characteristics. As such, the connector interference was not noticed. To assure issues such as this are detected in the SLA components, the .STL files must be created from the same 3-D database that will be used to produce the engineering drawings.

Probably the single most important lesson learned from the above experiences is that the SLA components are needed early in the design process. All of the above design errors could have been corrected at Pilkington before assembly and shipping. If the SLA components had been built two months earlier, to the exact hardware configuration, and trusted by the IPT members, these anomalies would never have been issues.



CAPTIVE FLIGHT TEST SEEKER

V. TACTICAL SEEKER ANALYSIS AND LESSONS LEARNED

After a successful CFT, all effort shifted to the design of the tactical seeker. The most challenging design change would be downsizing the aft seeker assembly from 7.50 to 6.55 inches. Less room would be available for electronics, cables and gas bottles. In addition, moving the mounting platform for the pre-amp electronics from the flat bottom of the optics housing to the round dewar housing was being considered. Moving the pre-amp would enable LMFS to enlarge their pre-amp package thus allowing for additional needed electronics. It would also require a total redesign of the package.

When the design had reached a point that was considered a feasible tactical design, building the associated SLA components was initiated. Approximately 50 individual SLA components were built and delivered to the Seeker IPT. The benefits derived from being able to assemble these parts, run gas lines and cables, observe anomalies, suggest design changes, etc. were innumerable.

One required design change noticed was that the joint between the forward and aft sections of the seeker had to be moved forward. This was due to an obstruction between the dewar housing and the nut plates that would allow connection to the aft seeker section. In addition, it was evident that additional access panels would be required to allow hook up of gas lines and cable connectors, after the two sections were mated together.

With program costs being estimated at $100,000.00 per day, the Seeker IPT believes the long term savings due to the SLA models made them worth their weight in gold. The SLA components were doing what they were designed to do. They were identifying problems early on, before metal was being cut. This is the true cost and schedule savings to any program. The SLA models cannot be considered the only reason these problems were found early. The IPT had employed an extremely powerful CAD station as well as very competent engineers. However, no one will disclaim the immense benefit derived from having SLA components of actual hardware to access design.

VI. SECOND TACTICAL SEEKER

The design changes initiated due to analysis of the tactical seeker SLA components had effectively made them obsolete. As the design of the seeker continued to evolve, it became apparent that a second iteration of SLA models of the tactical seeker would be needed. These models would be used for writing assembly procedures, designing and inspecting special tooling and holding fixtures, routing gas lines and cables, and other final production planning activities prior to assembling actual hardware.

Currently, SLA components of the forward seeker assembly are about 90 percent complete. The forward seeker assembly includes the optics, gimbals, detector dewar assembly, dome, and impact fuse sensor. The SLA components of the inner gimbal have been assembled to the SLA components of the optics housing at SRT. The assembly of these components was completed using SRT's assembly procedures and special tooling. Cables and gas lines have been routed and seem to fit as expected. The Seeker IPT now plans on constructing the assembly procedures for Raytheon and verifying them in the same manner.

Work is continuing on SLA components of the forward seeker assembly. When complete, effort will switch to the components of the aft seeker assembly which includes the gas bottle, bulkhead, and electronics assemblies. At that time, final production assembly procedures and tooling will be verified as the SLA components of the complete seeker are assembled.

One of the most important discoveries, directly attributable to the SLA components, has just been made. One of the most difficult integration steps to be completed at Raytheon is to mate the LMFS preamp electronics and focus the detector dewar assembly. On March 17, 1997 the SLA models of the new LMFS preamp and preamp cover were completed. This time, however, the SLA components of the preamp were built from the same database that would produce the engineering drawings. When trying to assemble these SLA components, a mechanical interference was noticed that made assembly impossible. The interference error was discovered before any metal parts were built. A redesign was initiated by LMFS immediately, resulting in minimal, if any, delays to

schedule. Finding this anomaly later, in the design process, would have meant astronomical impacts to both cost and schedule.

It should be noted here that typical interference checks on a CAD station would not have found the anomaly described here. The reason being, when assembled there was no interference. The interference occurred while sliding the pre-amp cover onto the pre-amp electronics. Since CAD software normally does not depict movement, it would never have shown that the actual assembly process was impossible.

VII. OTHER EFOGM SLA EFFORT

It seemed obvious, after the success experienced with the SLA parts during the CFT phase, that SLA components of other missile sections would be beneficial during the tactical phase. Discussions began with the EFOGM PMO Hardware Team concerning this subject. Work began on building SLA components of the aft section of the EFOGM tactical missile in April, 1996.

The aft section includes the control actuation section (CAS), the fiber optic cable and dispenser assembly, the hot plate assembly, electronics and various other pieces of hardware. Raytheon requested that the fairing that housed the CAS be built first. The fairing is a very complex part and discussions were ongoing with the vendor concerning manufacturing methods. This SLA component was provided, as well as the entire aft section, within the next four weeks.

After the aft section was completed, effort switched to building SLA components of the warhead section. This included an envelope of the warhead assembly and its mounting hardware. Of concern was a complex bracket that holds the canted warhead in place. The bracket was a point of discussions with vendors at that time. A Government conception of the bracket was built to aid in these discussions. These components were delivered within two weeks of starting the build.

Not being intimately familiar with the design details in missile sections, other than the seeker, the authors can not expand greatly on detailed benefits derived from these SLA components. However, since delivering these parts to the respective IPTs, a steady stream of praise for the SLA parts has been received. The most commonly referred to attribute, from both Government and contractor

representatives, is the SLA component's ability to simplify discussion. The inherent hardware features of the SLA component, by far, out produce the standard engineering drawing in problem definition and resolution.

The EFOGM PMO has also presented another request for SLA support. A joystick on the gunner's console of the Fire Unit was ergonomically unacceptable. It was requested that a prototype of a MICOM designed joystick be produced. The redesigned joystick was a product of the Missile Guidance and Structures Directorates of the U.S. Army Missile Command (MICOM), Research, Development, and Engineering Center (RDEC). The joystick was built on the SLA, and then sent to the System Engineering and Production Directorate (SEPD), Prototype Division to have some final machining done and threaded inserts added. The final product was then installed on the fire unit simulator and performed quite well during gunner testing. As a result, it is now planned to build an additional thirty joysticks, with some refinements and modification, on the SLA. These joysticks will be installed on actual fire units and delivered as part of the EFOGM Advanced Concept Technology Demonstration.

VIII. SUMMARY

The EFOGM IPT and SLA efforts were learning experiences for both the Government and industry. EFOGM was one of the first major project offices at MICOM to fully implement Integrated Product and Process Development as well as the first program to utilize the MICOM SLA to produce such a large number of parts and assemblies. In the beginning of the SLA program, it was unclear what benefits, if any, SLA could provide to the IPT environment. But once the IPT members got the SLA parts in hand, they began to discover small but significant design problem and were able to start solving these problems before they dramatically affected program costs or schedules. The kinds of design problems discovered were the ones that are difficult to identify by examining and analyzing a CAD database. They were also the kind of problems that seem to plague a program during that difficult leap from the relatively inexpensive CAD environment to the real world of hardware. Many of these problems stemmed from the number of subcontractors and interfaces required to develop and fabricate the seeker. The SLA was used to bridge the gap between these contractors and the Government to smooth the often rough road to flight hardware.

As the EFOGM SLA effort evolved, there were valuable lessons learned. The first was that the SLA parts need to be built early in the design process to give the designers time to analyze them and discover required changes before further effort is given to designing higher assemblies or fabricating metal prototypes. The second lesson learned was that the SLA parts need to be built directly from the CAD database. This gives the designers the confidence that the SLA parts are accurate prototypes of the actual hardware. This confidence leads to a more serious analysis of the design and results in more problems being solved earlier in the program.

The EFOGM IPPD and SLA efforts clearly illustrate the benefits of partnering the personnel and assets of industry with those of Government. The Government's direct participation on the EFOGM Seeker IPT was the key to identifying the availability of the MICOM SLA lab. This partnership has resulted in both cost and schedule savings to the EFOGM PMO.

BIOGRAPHY

The SL lab, described in this report, is located at the U.S. Army Aviation and Missile Command (AMCOM), Redstone Arsenal, in Huntsville, Alabama. Mr. C. Derrick Minor is employed in the AMCOM Missile Research, Development and Engineering Center (MRDEC), Systems Engineering and Production Directorate (SEPD), Production Engineering Division (PED). Mr. Minor supports the EFOGM PMO. His primary responsibility is to provide production and manufacturing support to the Team EFOGM Imaging Infra Red Seeker IPT. Mr. Minor also manages and operates the AMCOM SL lab where all parts discussed in this report were built. For additional information, the author can be contacted as noted below:

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